Development of a novel highly granular hadronic calorimeter with scintillating glass tiles

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On behalf of CEPC Calorimeter Working Group

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Motivations

• CEPC physics programs
  • Hadronic decays of Higgs/Z/W bosons: abundant hadrons (<10 GeV) within jets

• CEPC 4\textsuperscript{th} concept detector: crystal ECAL + scintillating glass HCAL
  • A leap in terms of sampling fractions
  • Aim to improve the energy resolution: esp. the hadronic resolution
Motivations

- CEPC physics programs
  - Hadronic decays of Higgs/Z/W bosons: abundant hadrons (<10 GeV) within jets
- CEPC 4th concept detector: crystal ECAL + scintillating glass HCAL
  - A leap in terms of sampling fractions
  - Aim to improve the energy resolution: esp. the hadronic resolution
  - Physics performance goal: Boson Mass Resolution (BMR) 4% → 3%

Dan Yu (IHEP)
Outline

Scintillating glass HCAL

Physics motivations → Design → Performance

CEPC Full Detector + PFA → HCAL alone simulation

Hardware → Measurements + Tile simulation
Outline

• Simulation of HCAL with scintillating glass tiles
  • Performance with single hadrons: hadronic energy resolution
  • Varying thickness of glass tiles and steel plates

• Studies on a single glass tile
  • MIP response: optical simulation and cosmic ray test
  • Uniformity scan with varying tile size
  • Estimated performance

• Scintillating glass material R&D
  • Measurements of scintillating glass samples

• Summary
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• Summary
HCAL setup in Geant4 simulation

- Geometry: a la CALICE-AHCAL
  - Transverse plane: $108 \times 108 \, cm^2$
    - Tile size: $3 \times 3 \, cm^2$
  - 60 longitudinal layers, each with
    - Scintillator: 3mm
    - PCB: 2mm
    - Absorber (steel): 20mm

- Scintillator materials
  - Plastic scintillator as baseline reference
  - Replace plastic scintillator with scintillating glass
    - Component: $B_2O_3 - SiO_2 - Al_2O_3 - Gd_2O_3 - Ce_2O_3$
    - Density = 4.94 $g/cm^3$

Note: HCAL with 40 layers in CEPC CDR as baseline. Hereby use 60 layers to evaluate leakage effects
HCAL: plastic scintillator vs scintillating glass

- Incident particle: $K_L^0$
- Preliminary performance comparison
  - Same thickness of sensitive materials: 3mm
  - No energy threshold applied
- Scintillating glass: better hadronic energy resolution in low energy region ($<30$GeV)
  - Note that majority of hadrons in jets at CEPC are with low energy
- More details in the next pages
Impact of thickness to hadronic energy resolution

- Varying thickness: scintillating glass tiles and steel plates
  - Each layer fixed with $\sim 0.12\lambda_I$: the same as AHCAL (3mm plastic tile, 20mm steel)

- Energy threshold significantly impacts hadronic energy resolution
- The empirical formula $\left( \frac{A}{\sqrt{E(GeV)}} + C \right)$ can not well describe curves
  - (Note the $\chi^2/ndf$ values) Not fully follow the Poisson distribution

Threshold=0 MIP

Threshold=0.5 MIP

Incident particle: $K_L^0$
Impact of thickness to hadronic energy resolution

- Varying thickness: scintillating glass tiles and steel plates
- Extraction of stochastic and constant terms

**Stochastic term vs. glass thickness**

- Threshold=0 MIP
- Threshold=0.5 MIP

**Constant term vs. glass thickness**

- Threshold=0 MIP
- Threshold=0.5 MIP

- Energy threshold has a significant impact on the energy resolution
- With the 0.5 MIP threshold, resolution will not be improved when glass thicker than ~0.08 $\lambda_I$
- Higher threshold significantly degrades the constant term
- Lower threshold would always be desirable for better resolution
Categorize energy depositions

- Categorize energy depositions of hadronic showers: EM, hadronic, invisible

- EM energy deposition usually detected with higher efficiency
- EM component fraction: incident energy dependent
- EM/hadronic energy depositions: non-Gaussian fluctuations

Yong Liu (IHEP)
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MIP response: cosmic-ray test

- Glass sample size: 4.5×4.5×3.5 mm³
- MIP response: 274 p.e./MIP
- Plastic scintillator triggers cover larger area than sample does, some cosmic rays cross part of the sample

Detected photons at SiPM: 273.8 p.e./MIP

Chi² / ndf: 13.61 / 16
Prob: 0.6277
Constant: 306.2 ± 28.0
MPV: 273.8 ± 3.3
Sigma: 19.19 ± 1.65
MIP response: optical simulation

- **Simulation setup**
  - Scintillating glass \((4.5 \times 4.5 \times 3.5 \text{mm}^3)\)
  - \(6 \times 6 \text{mm}^2\) SiPM
  - Small air bubbles are included
  - 1 GeV mu- (regard as MIP particle)
  - Vertical incidence in tile center

- Properties of scintillating glass
  - Component: \(B_2O_3 - SiO_2 - Al_2O_3 - Gd_2O_3 - Ce_2O_3\)
  - Density: 4.94 \(g/cm^3\)
  - Refractive index: 1.67
  - Transmission: 63%
  - Emission peak: 394 nm
  - Light yield: 881 ph/MeV
  (All data based on measurements)

- MIP response
  - Energy deposition: 2.0 MeV/MIP
  - Detected photons: 263 p.e./MIP

- The difference between simulation and test result: \(\sim 4\%\)
Uniformity scan for a scintillating glass tile

- Projected performance of a realistic AHCAL tile size
- Assumption: larger tile properties remain the same as small glass samples
- Larger tile size leads to less detected photons and more significant non-uniformity

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Incident particle: mu-change hit position (0.5mm step)
Impact of scintillating glass tile size

- Assumption: larger tile properties remain the same as small glass samples
- Vary transverse size, fixed tile thickness at 3 mm (AHCAL baseline design)

- Realistic parameters: ~65 p.e./MIP, using large size 6×6 mm² SiPM
- Ideal parameters: ~160 p.e./MIP → possible to use smaller SiPM
- Next plans:
  - Improve uniformity through tile-designs: “SiPM-on-Tile” is a feasible option
  - Scintillating glass R&D: improve both density and light yield
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• Summary
Glass Scintillators R&D Group

GS Production
- Development
- Mass production

GS Research
- Optical test
- Mechanical test
- Irradiation test

GS HCAL Design
- Simulation
- SiPM Research
- Single Tile Test

GS Application
- Unclear Detection
- Others

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Beijing Glass Research Institute
北京玻璃研究院

China Building Materials Academy
中国建筑材料研究院

China Jiliang University
中国计量大学

Harbin Engineering University
哈尔滨工程大学

Harbin Institute of Technology
哈尔滨工业大学

Sichuan University
四川大学
Measurements of scintillating glass samples

- Comprehensive measurements of key properties
  - Transmission/emission spectra, light yield and decay time
- Over 30 pieces of scintillating glass have been tested, most of which have poor performance
- The best performance glass with the composition: $B_2O_3 - SiO_2 - Al_2O_3 - Gd_2O_3 - Ce_2O_3$

Zhehao Hua (IHEP)
Measurements of light yield

\[ LYS = \frac{\text{Mean}_{\text{energy} \times 1000\text{keV}}}{\text{Mean}_s \times \text{PDE}_w \times \text{PCE} \times \text{Energy}} \]

- #2: photon=146, LY=536 ph/MeV
- #3: photon=185, LY=680 ph/MeV
- #4: photon=180, LY=660 ph/MeV
- #5: photon=192, LY=705 ph/MeV
- #6: photon=219, LY=802 ph/MeV

Zhehao Hua (IHEP)
Transmission spectrum, emission spectra and decay time

- Transmittance of samples can reach up to **78%**
  - air bubbles, heavy metal ratio will affect its transmittance
- Emission peak is around **393 nm**
  - can be matched with the detector band by adjusting the composition
- The decay time of GS5 is **354 ns (18%)**, **760 ns (82%)**

Zhehao Hua (IHEP)
Measurement results of scintillating glass samples

<table>
<thead>
<tr>
<th>Number</th>
<th>Density (g/cm³)</th>
<th>Transmittance (%)</th>
<th>Light yield (ph/MeV)</th>
<th>Energy Resolution (%)</th>
<th>Decay time (ns)</th>
<th>Emission peak (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>~4.5</td>
<td>50</td>
<td>546</td>
<td>30.84</td>
<td>273,1004</td>
<td>394</td>
</tr>
<tr>
<td>#2</td>
<td>~4.5</td>
<td>78</td>
<td>536</td>
<td>37.87</td>
<td>334,939</td>
<td>392</td>
</tr>
<tr>
<td>#3</td>
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<td>680</td>
<td>29.41</td>
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<td>393</td>
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<tr>
<td>#4</td>
<td>4.65</td>
<td>74</td>
<td>660</td>
<td>31.82</td>
<td>308,1363</td>
<td>396</td>
</tr>
<tr>
<td>#5</td>
<td>4.94</td>
<td>64</td>
<td>705</td>
<td>27.97</td>
<td>354,760</td>
<td>392</td>
</tr>
<tr>
<td>#6</td>
<td>4.53</td>
<td>67</td>
<td>802</td>
<td>26.77</td>
<td>318,1380</td>
<td>393</td>
</tr>
</tbody>
</table>

- The light yield of scintillating glass sample could reach 800 ph/MeV (until December 2021)
- Latest sample measurement result: light yield reached 1600 ph/MeV, but density < 4 g/cm³
- Next plans
  - Improve both light yield (2000 ph/MeV) and density (6 g/cm³)

Zhehao Hua (IHEP)
Summary and prospects

• A novel HCAL concept with high-density scintillating glass
  • Aim to improve energy resolution, especially hadronic energy resolution

• Scintillating glass HCAL performance in simulation
  • Hadronic energy resolution versus glass thickness

• Studies on a single glass tile
  • MIP response: cosmic-ray test and simulation
  • Impact of uniformity and tile size

• Measurements of scintillating glass samples
  • Transmission/emission spectra, light yield, energy resolution and decay time

• Prospects
  • To further improve the energy resolution: “Software compensation” or “Dual-readout” technique
  • Improve uniformity of a scintillating glass tile through tile-designs
  • Scintillating glass R&D: improve both light yield and density, develop large-sized samples
Backups
Definition of energy resolution

- Calibration constant: 0.086
- Fit range: (-1σ, +1σ)
- Energy resolution: \( \frac{\sigma}{E_{beam}} \)

Incident particle: 20GeV \( K_L^0 \)
HCAL: evaluate leakage effects

- Geometry size
  - Baseline: 108cm×108cm×60layers(~1.5m)
  - Ideal: 540cm×540cm×300layers(~7.5m)
- Incident particle: kaon0L (1-100 GeV)

- The impact of shower leakage to energy resolution in the 60 layer is estimated (~1% level)
Homogeneous HCAL: energy deposition with $K_L^0$

Categorize energy depositions: EM, hadronic, invisible
Homogeneous HCAL: energy deposition with $K_L^0$
Calculation of light yield

---**Absolute light yield**: The formula of the light yield: \( \text{LY}_s = \frac{\text{Mean}_\text{energy} \times 1000\text{keV}}{\text{Mean}_s \times \text{PDE}_W \times \text{PCE} \times \text{Energy}} \)

Calculated by different Almighty peak of radioactive source, the light yield of #6 glass is **802 ph/MeV**;

---**Relative light yield**: Calculate the relative light yield of glass through BGO standard crystal, the light yield of #6 glass is **845 ph/MeV**;

---The light yield of the glass calculated by the two methods is the same.

By Zhehao Hua